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Sex Differences in Valgus Knee Angle During a Single-Leg Drop Jump

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Context: Sex differences in lower extremity landing mechanics and muscle activation have been identified as potential causative factors leading to the increased incidence of anterior cruciate ligament injuries in female athletes. Valgus knee alignment places greater strain on the anterior cruciate ligament than a more neutral alignment. Gluteus medius (GM) activation may stabilize the leg and pelvis during landing, limiting valgus knee motion and potentially preventing anterior cruciate ligament injury.

Objective: To determine if frontal-plane knee angle and GM activation differ between the sexes at initial contact and maximal knee flexion during a single-leg drop landing.

Design: Between-groups design.

Setting: Motion analysis laboratory.

Patients or Other Participants: Thirty-two healthy subjects between the ages of 18 and 30 years.

Intervention(s): The independent variables were sex (male or female) and position (initial contact or maximal knee flexion).

Main Outcome Measure(s): Frontal-plane knee angle and GM average root mean square (aRMS) amplitude.

Results: At initial contact, women landed in knee valgus and men landed in knee varus ($P < .025$). At maximal knee flexion, both men and women were in a position of knee varus, but the magnitude of varus was less in women than in men ($P < .025$). The GM aRMS amplitude was greater at maximal knee flexion than at initial contact ($P < .025$); however, male GM aRMS did not differ from female GM aRMS amplitude at either position ($P > .025$).

Conclusions: Women tended to land in more knee valgus before and at impact than men. The GM muscle activation did not differ between the sexes and, thus, does not appear to be responsible for the sex differences in knee valgus. The excessive valgus knee angles displayed in women may help to explain the sex disparity in anterior cruciate ligament injury.

Key Words: biomechanics, kinematics, landing, electromyography, anterior cruciate ligament

Anterior cruciate ligament (ACL) injuries are receiving a great deal of attention because of the incidence of injury, not just in the athletic population but also in recreationally active individuals.[1] Women are 2 to 4 times more likely to sustain an ACL rupture than their male counterparts involved in the same sports.[2] Additionally, women are 3 times more likely than men to sustain an ACL rupture due to a noncontact mechanism rather than a contact mechanism.[2,3] In order to better understand and identify the reasons women sustain more noncontact ACL injuries than men, it is important to examine potential mechanical and neuromuscular factors affecting the knee joint complex. By uncovering differences between men and women, injury prevention programs and prescreening protocols can be developed in hopes of minimizing the number of ACL ruptures.

High-risk maneuvers linked with noncontact ACL injury include sudden deceleration while cutting or pivoting and landing from a jump.[4,5] The position of the lower extremity while completing these tasks is thought to be a factor contributing to ACL rupture.[4,6,7] Knee joint valgus is often implicated as a hazardous position for the ACL[8–11] and has recently been linked to ACL injury risk.[12] Valgus loading can increase relative ACL strain[13] and may reach levels high enough to cause ligamentous failure.[11] Because women display greater knee joint valgus than men,[9,10,12] valgus positioning may help to explain the sex disparity in noncontact ACL ruptures. Although several groups[9,10,12] have previously examined sex differences in knee joint valgus during a double-leg drop jump, evidence suggests that landing on a single limb is one of the most common ACL injury mechanisms[6,7] and, thus, deserves particular attention.

Dynamic stability is provided to the knee joint by surrounding musculature. Several authors[14–17] have examined the influence of ACL agonists (hamstrings and gastrocnemius) and antagonists (quadriceps) on knee joint position. Little attention has been paid to adjacent joint musculature at the hip, which may provide additional dynamic stability at the knee. The gluteus medius (GM) is known to stabilize the pelvis during a single-leg standing position and acts to internally rotate and abduct the femur.[18,19] Contraction of this muscle prevents contralateral hip drop and ipsilateral genu valgus, also known as the Trendelenburg position. Athletes with a weaker GM may not effectively resist adduction of the femur, potentially increasing knee valgus and thereby placing strain on the ACL.

Our purposes were to determine whether women land in greater knee valgus than men during a single-leg drop landing and to determine if GM activation differs between the sexes. We hypothesized that women would display greater knee valgus angles and less GM activation than men.

METHODS

The experimental design was a 2 $\times$ 2 factorial. Independent variables were sex (male or female) and position (initial contact [IC] and maximal knee flexion [MKF]). The 2 dependent variables of interest were frontal-plane knee angles (valgus or varus) and GM average root mean square (aRMS) amplitude. The knee flexion positions were incorporated as independent variables so that we could examine our dependent variables at different points during the landing task.

Subjects

Thirty-two healthy subjects (16 men: age = 24 $\pm$ 5 years, height = 182.3 $\pm$ 6.1 cm, mass = 84.6 $\pm$ 9.8 kg; 16 women: age = 21 $\pm$ 6 years, height = 163.3 $\pm$ 6.4 cm, mass = 62.1 $\pm$ 9.1 kg) volunteered to participate. Volunteers had not suffered any previous lower extremity injury and were not currently suffering any lower extremity injury that would prevent them from completing a single-leg drop landing. The physical activity level of the subjects was not assessed and, therefore, is unknown. This study was approved in advance by the University's Human Investigation Committee. Each subject signed an informed consent form before participating.

Instrumentation

The movements of the lower extremity segments were tracked with a 10-camera Vicon motion analysis system (model 624; Oxford Metrics Ltd, Oxford, United Kingdom) collecting at 120 Hz. Both static and dynamic calibrations were performed, and residuals of less than 2 mm from each camera were deemed acceptable.

Subjects landed on a force platform (model OR 6-7; Advanced Medical Technology, Inc, Watertown, MA), which was located in the middle of the capture volume for the cameras and used to collect ground reaction force data. Ground reaction force data were collected at 1080 Hz and were synchronized with the Vicon system for simultaneous collection. Force-plate data were filtered using a low-pass, anti-aliasing filter with a cutoff frequency of 1000 Hz.

Surface GM electromyography (EMG) was collected using the MA-300-16 system (Motion Lab Systems, Inc, Baton Rouge, LA) interfaced with the Vicon system for recording. Signals were pre-amplified with double differential EMG electrodes (Motion Lab Systems, Inc) and collected at 1080 Hz. The input impedance of the amplifier was $>$100 megaohms, with a common mode rejection ratio of $>$100 dB and a signal-to-noise ratio of 50 dB.

Illumination, video data collection, and analog-to-digital conversion of transducer input (force plate and GM EMG data) were synchronized and controlled by the Vicon 370 Datastation, which was interfaced and controlled by a Pentium-based PC running the Windows NT operating system (Microsoft Corp, Redmond, WA).

Testing Procedures

Subject Preparation. Subjects' height (cm), mass (kg), leg length (cm), anterior superior iliac spine to anterior superior iliac spine width (cm), knee and ankle midjoint widths (cm), and anterior superior iliac spine to greater trochanter distance (cm) were measured and recorded to estimate the center of rotation of the ankle, knee, and hip. Sixteen retroreflective surface markers were placed on the skin using double-sided tape (Figure 1). Markers were positioned on both lower limbs according to the Vicon Clinical Manager protocol over the anterior superior iliac spine, posterior superior iliac spine, lateral midthigh, lateral femoral condyle, lateral midcalf, lateral malleolus, posterior calcaneus, and head of the second metatarsal. Surface EMG electrodes were placed on each subject's dominant limb, the limb the subject preferred to land on, over the muscle belly of the GM.[20]

Drop Landing Procedures. In order to simulate the deceleration encountered during athletic participation, subjects were asked to perform a drop landing task from a 60-cm height (Figure 2). To orient participants with the landing task, each subject was asked to perform 3 to 5 practice trials. Once subjects were comfortable with the task, they were asked to perform 6 successful trials. A successful trial was defined as one in which the subject dropped down (ie, did not jump down) on the dominant leg to the force platform, ''stuck'' the landing for approximately 2 seconds, and did not touch the ground with the opposing limb. A standing single-leg static trial was taken before the drop landing trials for use in normalizing the collected EMG data. This required subjects to stand still on the dominant limb on the force platform for 5 seconds.

Data Analysis

Frontal-Plane Knee Angles. Marker trajectory data were filtered using a Woltering filter (Vicon) and frontal-plane knee joint angles were calculated using rigid body analysis with Cardan angles (Plug-In Gait, Vicon). Frontal-plane knee angles were identified at 2 points during the landing task: IC and MKF. Time of IC was defined as the point at which ground contact was first made with the foot, whereas MKF was defined as the peak knee flexion angle recorded upon landing on the force platform (Figure 3). Both IC and MKF were used only as markers to analyze frontal-plane knee-angle data. The frontal-plane knee angles for the 6 drop-landing trials were averaged and used in the statistical analyses.

Electromyography. The GM EMG data were band-pass filtered from 10 to 500 Hz and processed with a root mean square algorithm with a 3-millisecond window using AcqKnowledge software (BIOPAC Systems, Inc, Santa Barbara, CA). The GM RMS EMG was averaged for 100 milliseconds before IC and again for 100 milliseconds before MKF. The same time interval (100 milliseconds) was used to average GM root mean square EMG from the static trial. The GM aRMS amplitude data were normalized by dividing the trial averages by the GM aRMS amplitude recorded during the single-leg static trial data.

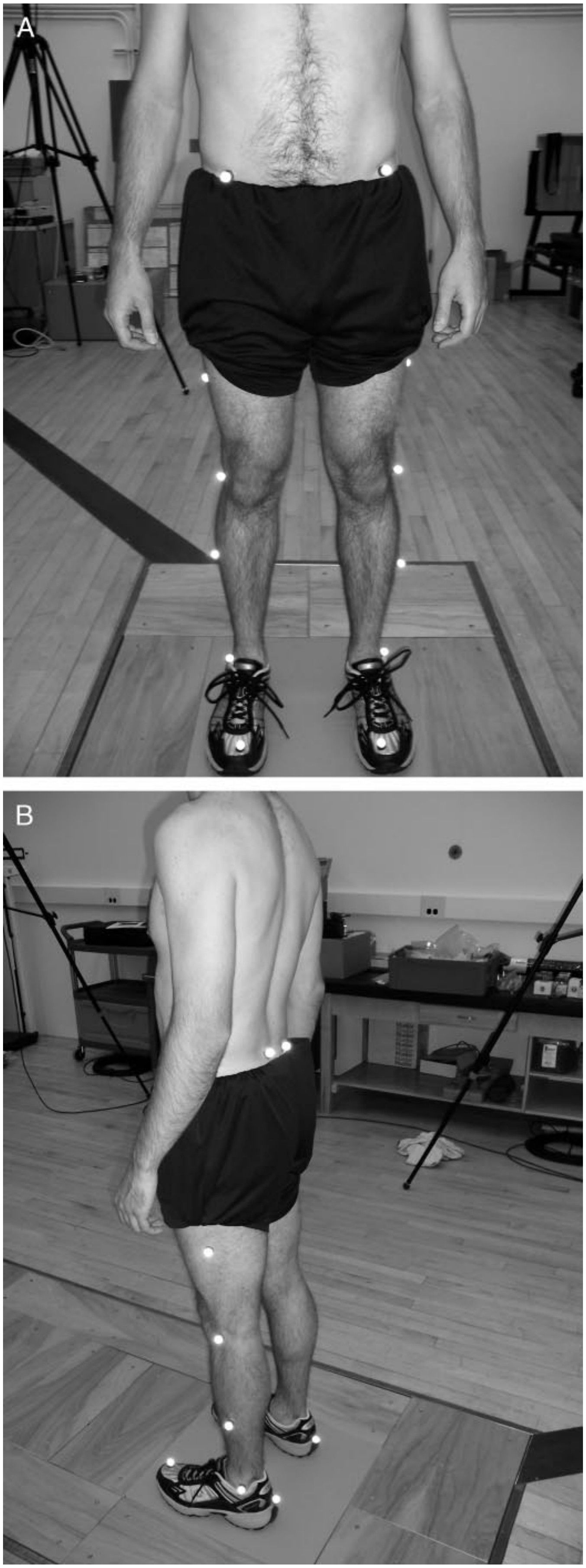

Figure 1A, B. Placement of the 16 lower body retroreflective markers.

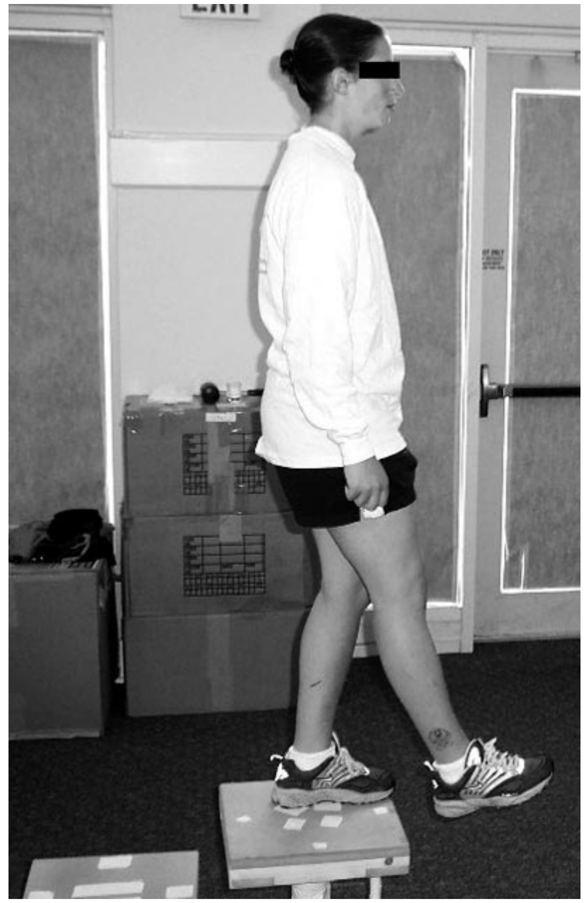

Figure 2. Starting position during a single-leg drop landing.

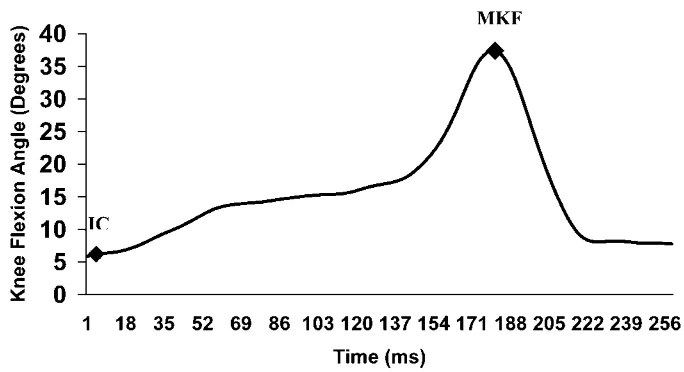

Figure 3. Maximal knee flexion (MKF) angle recorded from a single subject during the single-leg drop landing. Time of initial contact (IC) and MKF are identified on the graph.

Statistical Analysis

A 2 $\times$ 2 analysis of variance with repeated measures on position was calculated to determine if frontal-plane knee angles differed between groups. A separate 2 $\times$ 2 analysis of variance with repeated measures on position was computed to determine if GM aRMS amplitude differed between groups. Bonferroni multiple comparison procedures were used to make all post hoc comparisons. The a priori alpha level was set at $P \leq .025$ (Bonferroni correction) for all tests. We used SPSS (version 10.1; SPSS Inc, Chicago, IL) to perform all statistical analyses.

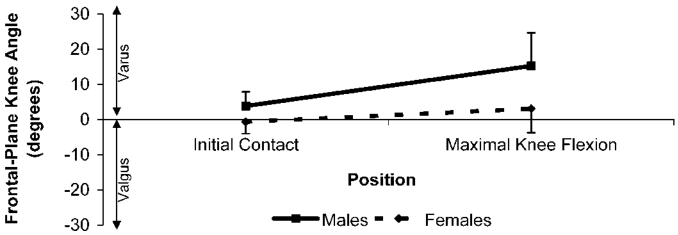

Figure 4. Frontal-plane knee joint angles at initial contact and maximal knee flexion for men and women. Negative values represent a valgus position and positive values represent a varus position. Women landed at initial contact in valgus, whereas men landed in varus ($P < .025$). Women landed in a more "relative" valgus position at maximal knee flexion than men ($P < .025$). Frontal-plane knee angles were greater at maximal knee flexion than at initial contact ($P < .025$).

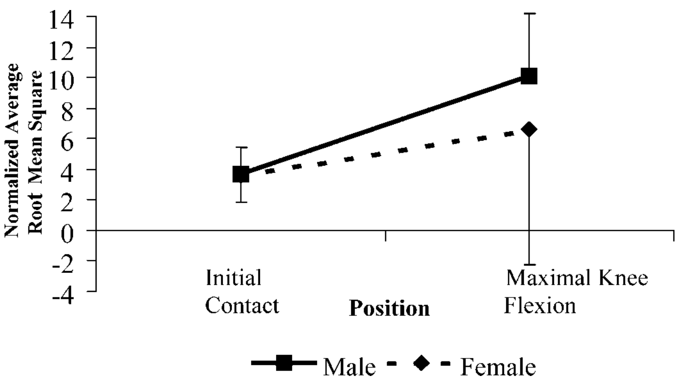

Figure 5. Normalized gluteus medius average root mean square amplitude data at initial contact and maximal knee flexion for men and women. No statistically significant differences were noted between men and women. Gluteus medius muscle activation was greater at maximal knee flexion than at initial contact ($P < .025$).

RESULTS

Frontal-Plane Knee Angle

Negative values represent valgus positioning, whereas positive values indicate varus positioning. A position-by-sex interaction was detected for frontal-plane knee angle ($F_{1,30} = 7.59$, $P = .01$). Main effects were detected for position ($F_{1,30} = 30.1$, $P = .0001$) and group ($F_{1,30} = 21.8$, $P = .0001$). At IC, women landed in valgus ($-0.651 \pm 3.32°$), and men landed in varus ($3.85 \pm 4.03°$) ($P < .25$). At MKF, men reached a greater varus position ($15.26 \pm 9.41°$) than women ($3.13 \pm 6.84°$) ($P < .025$) (Figure 4).

Gluteus Medius Activation

A main effect was detected for position ($F_{1,30} = 15.83$, $P = .0001$) but not for sex (men $= 6.94 \pm 7.11°$, women $= 5.09 \pm 3.43°$, $F_{1,30} = 1.94$; $P = .174$, $1 - \beta = 0.271$, $\delta^2 = 0.06$) when examining GM aRMS amplitude (Figure 5). Furthermore, no interaction effect was noted between group and position ($F_{1,30} = 1.95$, $P = .173$, $1 - \beta = 0.27$, $\delta^2 = 0.06$). The GM aRMS amplitude at IC (3.64 ± 1.69) was less than the GM aRMS at MKF (8.39 ± 7.03) ($P < .025$).

DISCUSSION

Limiting the valgus position of the knee during a single-leg landing could reduce strain on the ACL and in turn reduce the number of noncontact ACL injuries. Our results suggest that women land in greater knee valgus than men, but GM activation does not differ between the sexes.

A single-leg landing involving forceful valgus with the knee close to extension has been identified as a common mechanism of ACL injury.[6,7] Our findings demonstrate that during a single-leg landing, women displayed greater valgus knee angles than men. Similar evidence has been presented by Hewett et al[9,12] when subjects performed a double-leg drop jump. Women landed with larger maximal valgus knee angles and exhibited higher peak adduction loads[12] at the knee joint complex than their male counterparts. Because increasing valgus positioning by 5° from a neutral alignment can increase the load on the ACL by 6 times,[21] the finding that women land with greater knee valgus than men may help to uncover one of the underlying factors contributing to the sex disparity in ACL injuries.

We have identified that women were in knee valgus (whereas the men landed in knee varus) as soon as any contact was made with the ground (eg, before forces were transferred from the ground to the body), suggesting that women may be preprogrammed with an ineffective and potentially hazardous landing strategy. Furthermore, we noted that women remained in more ''relative'' valgus at the time of MKF and believe that this represents an inability of our female subjects to overcome their initial landing posture. Upon closer examination of our data, we found that 2 of our male subjects demonstrated a similar landing strategy to that of our female subjects (eg, landing at initial contact with a valgus knee angle equal to or above the mean of the females and remaining in more relative valgus at MKF). We suggest that individuals landing in knee valgus before ground contact may represent a preprogrammed strategy that possibly places them at risk for ACL injury. Further examination of this potentially detrimental landing technique may provide clinicians and scientists with a screening tool to identify athletes predisposed to future knee injury.

The landing technique employed by an athlete is critical, as it dictates how forces are distributed. Landing with greater knee valgus supports the notion that women may adopt a ligament-dominant strategy, relying on passive structures to resist and absorb ground reaction forces and promoting ligament failure.[9] Injury prevention programs focusing on dynamic control of knee motion in the sagittal plane and reduction of frontal-plane movement and torques may help to prevent ACL injury. Sportsmetrics, a plyometric training program, has been shown to effectively reduce varus and valgus torques and, thus, may be effective in diminishing the incidence of ACL injury.[22] Further understanding of how much frontal-plane motion in vivo is hazardous and whether valgus knee angle can predict ACL injury would be of value in order to better understand its importance in ultimately causing ACL failure.

No difference in GM muscle activation was observed between men and women. The GM is a primary hip abductor and is critical to pelvic stabilization; its dysfunction is felt to be associated with dynamic lower extremity malalignment (including knee valgus) during a single-leg stance.[23] Gluteus medius activation is altered in patients with ankle injury,[24,25] suggesting that proximal lower extremity musculature may play a role in more distal lower extremity joint injury. Furthermore, strengthening of the hip musculature in patients with patellofemoral pain and exhibiting excessive knee valgus, hip adduction, and hip internal rotation returned kinematics to normal.[26] We hypothesized that women would display less GM activation than men, preventing adequate pelvic stabilization during the landing task, promoting dynamic malalignment, and increasing the degree of knee valgus. Our data fail to support this hypothesis, suggesting that the GM musculature is not responsible for the observed difference in valgus knee angle. It may be that musculature directly acting on the knee joint complex (ie, quadriceps and hamstrings) is more important in limiting knee valgus, or it could be that the time of GM activation is of greater importance than the level of activation. It should be noted that women displayed lower levels of GM activation than men when performing a forward-jump maneuver.[27] Further research is necessary to understand whether the GM is of significance in controlling frontal-plane knee motion.

The increase in GM activation we observed with the increase in knee flexion angle during landing may be a strategy that helps to transfer forces from the lower extremity up through the trunk[28–30] or may have resulted from femoral movement from a more valgus to a varus position. During landing, a subject's total energy is transformed from potential to kinetic energy, which includes impact or ground reaction forces.[30] The landing technique usually involves movements that act to dissipate these forces.[30] At IC, the body has not started to decelerate and ground reaction forces have not yet transferred, which would explain the lower GM activation before IC. During soft and stiff landings, when comparing hip, knee, and ankle muscle moments, the greatest muscle moments occurred at the hip joint.[30] The hip musculature, including the GM, is required to maintain stability of not only the pelvis but also the trunk and upper body.[31] We hypothesize that the increase in GM activation is probably a response of the hip musculature trying to stabilize the hip in a neutral position and limit awkward hip and lower leg positions, such as extreme valgus, that could potentially endanger the limb.

LIMITATIONS

Although the methods we employed to establish joint kinematics in the current investigation are commonly used and deemed acceptable, it is important to acknowledge their limitations. A skin-based marker system and its associated motion artifact may not definitively predict underlying movement of the bones. Along similar lines, we acknowledge that sagittal-plane motion can influence frontal-plane motion using such techniques. As such, it is possible that if the knee flexion angles at each position were distinctly different between men and women, our measures of frontal-plane motion could represent a difference in knee-flexion angle, rather than a sex difference. The knee-flexion angles recorded at IC and again at MKF were similar for both men and women (Figure 6) and, thus, we are confident that our results do reflect sex differences in frontal-plane knee angles.

We did not assess the skill level of our subjects, which potentially could affect our results. Other authors[2] have noted skill level as a factor predisposing women to ACL injury. Although we cannot disregard that skill level may have played a role in the observed sex difference, both study groups were randomly selected.

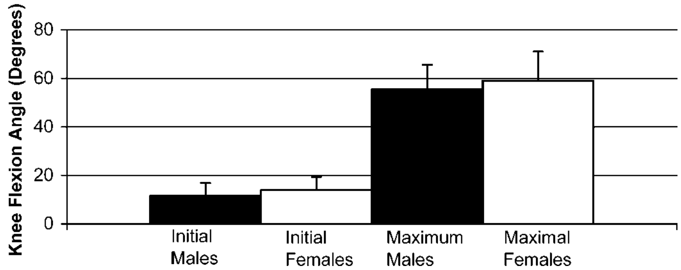

Figure 6. Average knee flexion angles for men and women recorded at initial contact (Initial) and maximal knee flexion (Maximal).

CONCLUSIONS

Women had a greater valgus knee angle at IC and remained in more relative valgus at MKF than men performing a single-leg drop landing. Based on our results, one could conclude that the tendency for women to remain in a greater relative valgus position than men throughout the landing may help to explain the sex disparity in ACL injury.

Gluteus medius muscle activation did not differ between the sexes and, thus, may not be critical in controlling frontal-plane knee joint motion.

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